PROPELLER DRIVE SYSTEMS AND TORSIONAL VIBRATION

Written *by Donald P. Hessenaur*

As aircraft engine prices continue to rise beyond the reach of most who would like to build and fly their own aircraft, many are turning to alternate power sources. This is not a new phenomenon. From the Wright brothers on, many have designed, built or converted engines to aircraft use. At one time or another engines have been used from automobiles, motorcycles, outboard motors and even snowmobiles, with varying degrees of success or failure.

AUTO ENGINE CONVERSIONS

Today many automotive engine conversions are appearing on the aviation scene. They are definitely a viable alternative. The automotive engine today is very advanced technically and relatively low in cost when compared to Lycomings and/or Continentals. Unfortunately, automotive engines are designed and optimized for the automobile and not for aircraft. Generally auto engines operate at a much higher RPM. The torsional vibration characteristics of a given engine, connected to a transmission, drive train and wheels, are quite different from that of the same engine, connected to an aircraft propeller. The damping action of the tires on the road and the inertia effects of the mass of the automobile are not even close to the damping/inertia effects of a propeller turning in air.

TORSIONAL RESONANCE

In recent years, I have developed a concern that many of the individuals and/or companies involved in the development of auto conversions do not seem to have an understanding of the problem of torsional vibration. I'm not saying that this is true in every case. Some appear to have a profound knowledge of torsional vibration but others seem to dismiss it as a minor problem. They feel all they need to do is just stick in a rubber damper, freewheel clutch or some other quick fix and maybe the problem will go away. My experience has been that torsional vibration just doesn't go away. It can be the life or death of an entire project, not only technically, but it can also lead to a financial black hole for the individuals or company involved! The potential for success in such a project would be much higher if the individuals involved knew what they were dealing with and would use valid aircraft engineering procedures during the design and development of an engine. Creativity and experimentation should be encouraged but one must also realize that 9 times out of 10, what was thought to be a new and original solution to a problem has probably been tried by a number of people in the past. The same laws of physics, dealing with torsional vibration, are still in effect today, as they were 20 to 50 years ago. I would be the first to admit. I do not have all the knowledge on vibration in rotating systems. Nevertheless, I have had some unique experiences with torsional vibration and other associated vibration problems. It is my hope that by relating them, someone will be saved from some grief.

FIRSTHAND EXPERIENCE

In the past I have had the opportunity to have worked on three interesting projects each of which involved torsional vibration problems to one degree or another.

The first was the Avian 2-180 gyroplane which was developed in Georgetown, Ontario, Canada in the early 60's. The performance and handling of this gyroplane has not been surpassed by any other in its class to this day.

The second was the BD-5 “Micro” kit aircraft developed in Newton, Kansas by Jim Bede in the early 70's.

The third was the RotorWay RW-133 helicopter engine developed by B.J Schramm in the mid-70's.

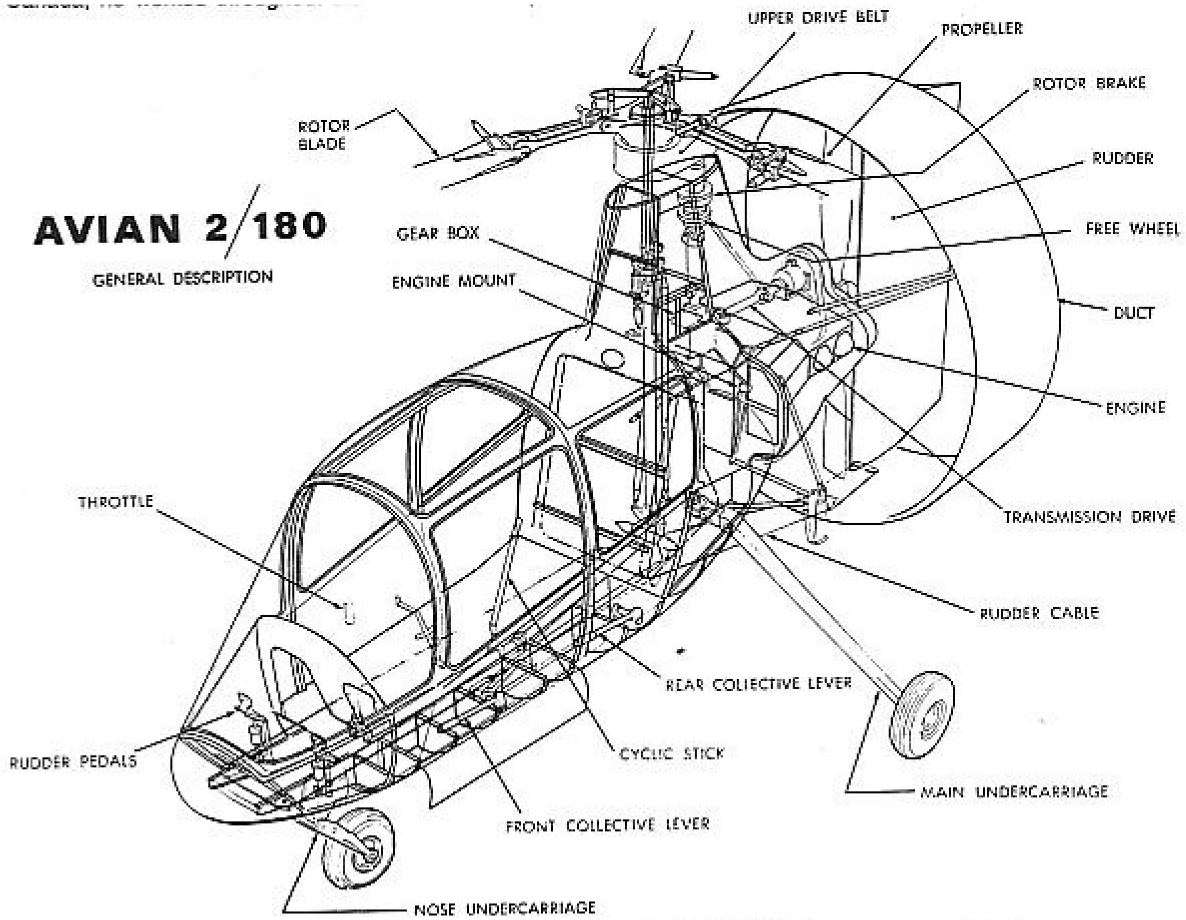
AVIAN VIBRATION ENCOUNTERS

The Avian gyrocopter was a pusher design with a ducted Hartzell propeller. The rotor was an articulated 3 bladed semi-rigid, high inertia design. For this reason, a substantial drive system was required for rotor spin-up. On the original prototypes there was a 3 inch wide, heavy duty, square toothed belt that transmitted engine power from a smaller driver sprocket to a large driven sprocket at the base of the rotor hub. Occasionally, during a spin-up, this belt was stretched by some horrendous load so that the belt teeth would no longer engage the teeth on the driven sprocket causing the belt to ride up on top of the sprocket teeth. The resulting high load on the sprockets caused the structure that supported the bearings to collapse (A round toothed HTD type belt would have eliminated the riding up problem of the square tooth belt but it had not as yet been developed in the early 60's.)

About this time, Avian started to develop and build their last prototype. It was totally redesigned and much improved in every way over the previous prototypes. One area of improvement was the rotor spin-up system. The upper belt width was increased to 4 inches and the structure that supported the sprocket bearings was made more substantial. A new hydraulic multi-plate clutch was designed with more torque capacity and mounted over the engine near the propeller end. This improved drive gave the new prototype absolutely phenomenal jump take-off performance. The gyroplane was capable of jump take-off to 50 ft. The problem of the upper bed drive had been solved by the brute strength approach, using a stiffer support structure along with a wider belt and sprockets. Nevertheless, as time went on other problems started to show up. The lower belt drive, which took power off the engine, seemed to flop a lot at various times. After a few spin ups the clutch would become very hot and eventually turn blue in color. If the cowling was removed, immediately after a spin-up the clutch would appear to have been red hot. The torsional loads going through the drive system appeared to be much higher than the original analytical numbers indicated. I had heard about torsional vibration during my college years but at the time it never hit me that the problem with the drive system involved torsional vibration. As far as I know, the clutch problem was never solved.

FLUTTER & VIBRATION TESTING

While at Avian I was assigned to work with a consultant who was hired to do ground vibration testing and a flutter analysis on our new prototype. This was a relatively new technology and he was the only person who did this kind of work at the time. Although he was from Tononto, Canada, he worked throughout the American aerospace industry. His equipment included a number of vibration shakers that were attached to the airframe, making it vibrate at various input frequencies. The shakers were controlled from a control panel. A number of magnetic vibration sensors were attached to the airframe, along with one that was hand held, so it could be moved around. These pickups were used to sense the resulting amplitudes of vibration at various points on the airframe. This information was then displayed on an oscilloscope. He was able to adjust the input frequency, so that various parts of the airframe would vibrate at their respective resonance frequency. The needles on the instruments, the door handle, the Plexiglas in the side window, a duct support structure or the rudder could all be made to vibrate at their individual resonance frequencies. It was really weird. In fact, it appeared downright mysterious to see this engineer adjust the input frequency and shake any part he wished on the airframe. He made a frequency survey of everything that resonated on the gyroplane. This was used to determine if anything resonated within the operating frequency range of the engine, drive system or rotor, which might cause a failure in the future. With this analysis, we found a number of parts that needed to be stiffened or redesigned so they would not vibrate or flutter in flight.



During the 3 days I worked with this engineer as his assistant, I received a wealth of knowledge about vibration and resonance in aircraft.

BEDE AIRCRAFT

I was interviewed and offered an engineering position with Bede Aircraft by Burt Rutan. My employment started on July 6, 1972. After the Avian years, my interest in the entire subject of vibration expanded and I became fully aware of torsional problems in rotating systems. Many spare hours were spent hitting engineering texts and reading numerous articles on the subject, including many by Molt Taylor. I was really curious as to how they had solved the torsional vibration problem in the BD-5.

During the first week at Bede, Les Bervin was flying the BD-5 every day. When it would come down after a flight, the mechanics would open up the engine compartment to take a look to see what was going on. It wasn't long before I realized there were a number of problems they were laying to deal with. The engine was having cooling and mixture problems while trying to maintain the EGTs and CHTs below redline. The problem that really caught my attention was the overheating of the belt and sheaves.

At that time they were running a snowmobile belt on variable ratio sheaves. The overheating clutch at Avian came to mind when I noticed these sheaves were quite discolored from the high temperatures involved.

TORSIONALS AT BEDE

During the following weeks they seemed to be doing a lot of ground testing. I had been assigned the responsibility for the weight and balance control for the BD-5 program, as I had done at Avian. Like the Avian 2-180, the BD-5 had a severe aft CG problem. One day they had been running the BD-5's engine on the ground for a period of time and all of a sudden there was a big explosion. The belt had disintegrated, with pieces all over the tarmac. These pieces of belt were as hard and bridle as bakelite plastic. As soon as I saw what happened, I knew the problem was torsional resonance. I mentioned this to the other engineers and they looked at me sort of strange. They thought I was joking and did not pay too much attention to my comment, since I was just the new engineer.

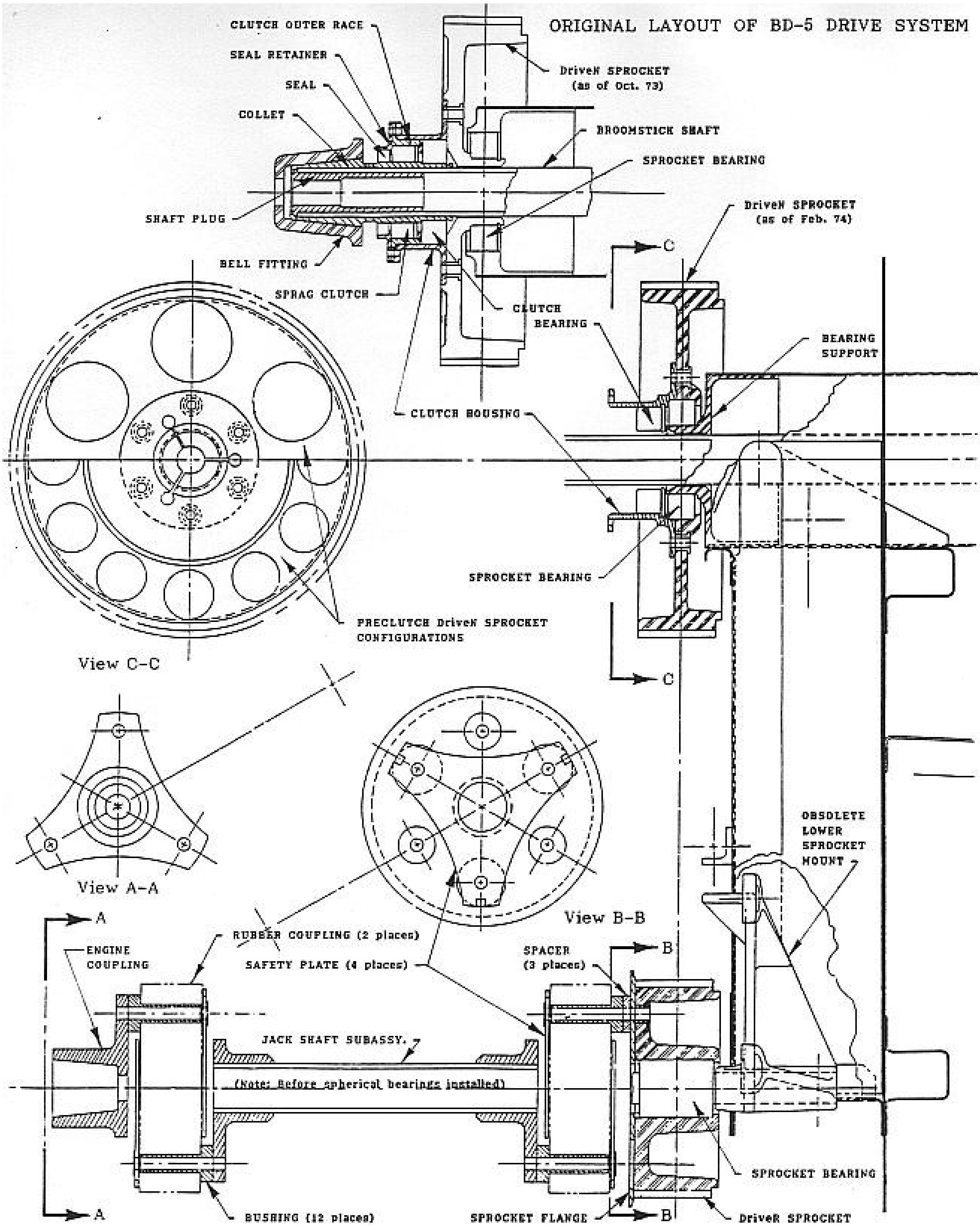
HTD UNIROYAL BELT

Soon after the belt incident some belt people were invited to come and look at our situation. The representatives brought a number of belts such as standard V, poly V and various toothed belts. One belt that I had never seen before caught my eye. It was a unique round toothed belt, a 6mm HTD belt. After all the problems associated with square toothed belts at Avian, when I saw that round toothed belt, I knew this was an exceptional design. It could be used on an aircraft and give much more reliability than one with square teeth. Best of all, the power loss was extremely low, since it ran at low friction levels, resulting in considerably less heat build-up.

About this time I was asked to start investigating various belt systems and get involved in the drive system and engine installation problems. Along with this assignment, I continued to head up a weight reduction program, particularly in the aft part of the ship. It was my intent to not only solve the drive system and engine installation problems but to save weight in those areas as well. Anything that could be done to remove weight, aft of the CG, would permit lead to be removed from the nose. So I started working on a new drive system, using the 8mm HTD belt. Once it was put together and running, it seemed at first to perform quite well, but I soon noticed there was a lot of flapping of the belt at certain RPMs. We tightened the belt as much as we could but the flapping just seemed to persist. Nevertheless, it seemed to solve the problem for the moment and Les Bervin put in a lot of flight time. Every once in a while we would have a failure but we would replace or repair the part and keep going. During this time we actually had more of a problem with the snowmobile engine. Various magazines were coming out with articles on the BD-5. It was becoming very popular and kit sales were climbing.

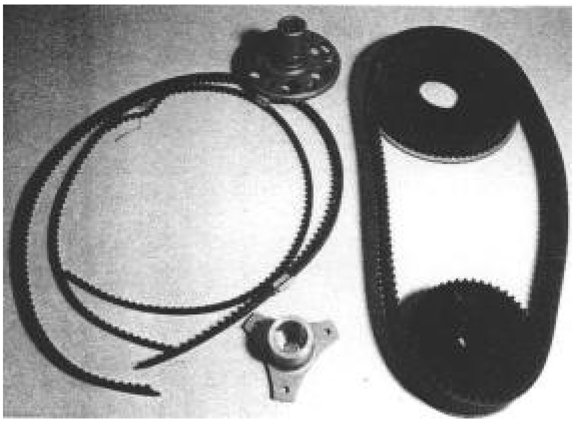
ENGINE MOUNT FAILURE

One significant event that occurred was the failure of the engine mount due to fatigue. The mount was welded up chrome-moly tubing and had a strange crystallized break. When I saw it, I knew it had something to do with the torsional vibration that was still in the system. A new heavier piece of tubing was welded in to make it stronger and beefier but during the next few flights it proceeded to break again. At this point a new heavier engine mount was fabricated and installed but soon after another failure occurred. This time the engine mount survived but the sheet metal channels that transferred the engine load into the fuselage, along with portions of the fuselage itself, were severely cracked. Also, numerous rivets were starting to work loose in the airframe. All that we had accomplished was to transfer and chase the problem from one area to another. The torsional problem was still with us. The biggest problem I had was that no one would believe me. At least the belt was holding up and no longer a problem.



MYSTERIOUS SHAFT FAILURE

The drive system difficulties were totally overwhelmed by the problems with the two stroke engine. To keep the planes flying for demonstrations and air shows, we were forced to place the highest priority on keeping the engines running. (If only the Rotax 562 had been available, we might have eliminated a major problem with the BD-5!) Cooling was a real difficult problem and one evening I and many of the engineering personnel stayed almost all night to find a solution. Burt was really frustrated with this cooling problem. In a last ditch effort, he got one of the giant portable electric shop fans, hooked it up to a large duct and then attached the duct to the open BD-S engine compartment. He felt if we couldn't get the engine to cool properly with this fan, there was no way we were going to get it to cool in the air. We ran the engine at full power and cycled the engine off and on a number of times. All of a sudden during one of the runs, something broke loose and the engine immediately went up to a very high RPM and seized. We found the propeller could turn freely without turning the drive belt or the engine. We looked all around and through everywhere and couldn't see where any break had occurred. No shaft had broken; nothing had failed that we could see. It was a real mystery.



BD-S HTD belt drive components Tests were run on various belt widths to establish useful life recommendations.

The drive system we had at that time used the HTD belt with the original upper main shaft. If I remember correctly, the O.D. of this shaft was about 3 inches and approximately 4 feet long. I am not sure of the wall thickness but it may have been .125 inches. This shaft had a machined bearing support fitting on each end, with the propeller mounted on the rear hub fitting and the HTD sprocket mounted on the front sprocket fitting. These end fittings were mounted to the inside diameter of the shaft, with three AN-4 bolts on each end, screwed radially into the shaft. The bolts were quite short so the threads went right up to the head, placing threads right in the shearing intersection between the fittings and the shaft itself. It was these 3 bolts at each end that transferred the torque from the HTD sprocket to the propeller hub at the rear. This was the configuration of the upper shaft when I arrived at Bede. Having bolts transfer torque in shear through the threaded area is not exactly a textbook design procedure but it had held for a year or more.

TORSIONALS STRIKE AGAIN

So we got the mechanic and started taking everything apart. When we pulled out the upper shaft, we found that all 6 bolts, 3 on each end, had failed precisely at the same time. Now this was weird or like black magic. You would think that if something was going to fail, maybe the rear end would be ready to go but the front end might break loose first, relieving the load, then the back end would not fail. But no, both ends of the 4 foot shaft failed precisely at the same time, with all 6 bolts failing the same way. They were all crystallized and appeared to have been working in there for some time.

By this time, Burt and the others had become believers in torsional resonance. Immediately we got on the phone, woke Jim Bede up and clued him in on what had happened. Within a week or so Jim brought in Al Beaufrere, a vibration expert from Long Island. I was assigned to work with him to solve the torsional problem. He came up with two different test drive systems. They were quite heavy and complicated but they did give us a direction in which to go. While Al was at Bede, I tried to learn all I could from him. This knowledge: combined with what I had picked up previously, gave us the insight that eventually led to a solution to our dilemma.

THE MOLT TAYLOR DYNAFLEX SYSTEM

After Al left, I started to design a new drive system, using the principles learned. It was about this time that many of the engineering staff were moved into the new Bede Product Development building. I was given an office with another engineer named Larry Heuburger, who I believe helped design the Derringer twin engine airplane. Larry knew Molt Taylor quite well and was able to persuade Jim Bede to let him design and build a small dynaflex coupling out of aluminum. I must say he did a beautiful job and came up with a real neat small dynaflex, which mounted right onto the engine. They used it with the HTD belt system and large upper shaft that I had running at the time. It appeared to successfully dampen out the torsional vibration. At the same time they were testing the dynaflex system I was coming right along with the design and fabrication of my new drive system.

I forget just how long they flew the Molt Taylor system but one day an in flight failure occurred and Les had to deadstick the plane in. With all the engine problems this was quite a common occurrence so it was no big deal. It was found that the dynaflex had broken loose from the engine. A closer examination revealed that the crankshaft had broken clean off. The break was completely crystallized and it was difficult to discern whether it was a torsional break or a lateral break. We were not able to determine why this failure occurred. It may have been due to the rocking couple of the engine. Unfortunately, this failure ended funkier work on the dynaflex system.

THE BROOMSTICK SHAFT

I had come to the conclusion that based on the information from Al Beaufrere, we needed to drastically lower the torsional frequency of the drive system by lowering its torsional spring constant. Stan Welles, our stress analyst, came up with a 6061-T6 aluminum shaft, with an outside diameter of 1 inch and a .095 inch wall thickness. This shaft came to be known as our "broomstick shaft". The same tubing size was used for both the upper main shaft and the lower jackshaft. Very soft rubber, donut type flexible joints were mounted on each end of the jackshaft. This lower shaft assembly transferred the power from the engine to the lower HTD sprocket while allowing for engine motion. The sprockets were made of a rag-filled bakelite type plastic by the Budd Corporation and are no longer available. They had wear characteristics, designed to be compatible with the HTD belt and had considerably less wear than anodized aluminum sprockets. Also they were lighter in weight. The lower sprocket was mounted on an adjustable casting that was mounted on the rear bulkhead of the engine compartment. The belt went up to the upper sprocket, which was attached to the forward end of the upper shaft.

The drive ratio was 1.6 to 1.0. Bearings within the sprockets took the belt loads, which were relatively low since the belt was not preloaded. There was no need to have a tight belt with a torsionally soft system. Since the upper main shaft was only 1 inch OD, two bearings were mounted along its length to tune out lateral vibrations. Another bearing was mounted off the rear hub to take out the propeller loads. (Later, after I left Bede, Dan Cooney added another bearing towards the rear, to more effectively take out gyroscopic propeller loads)

FRICTION JOINTS

The shaft end fittings on the lower jackshaft and the propeller hub on the upper shaft were attached with press-shrink friction fits. The fitting for the upper sprocket on the forward end of the upper shaft was a removable collet type friction fit. These friction fits were more than sufficient to carry the torque of the engine and were one of the design guidelines given to me by Al Beaufrere for joints subject to torsional vibration. This was a very, very lightweight system. The weight of the entire drive system was reduced by over 40 percent and this went a long way towards solving the aft CG problem in the BD-5. For test purposes, the prototype drive systems were designed and fabricated with zero safety factors. The first version of the "broomstick' drive did not have a freewheel clutch and when we first ran the system, we found out there was still much to be learned before the torsional problem was solved.

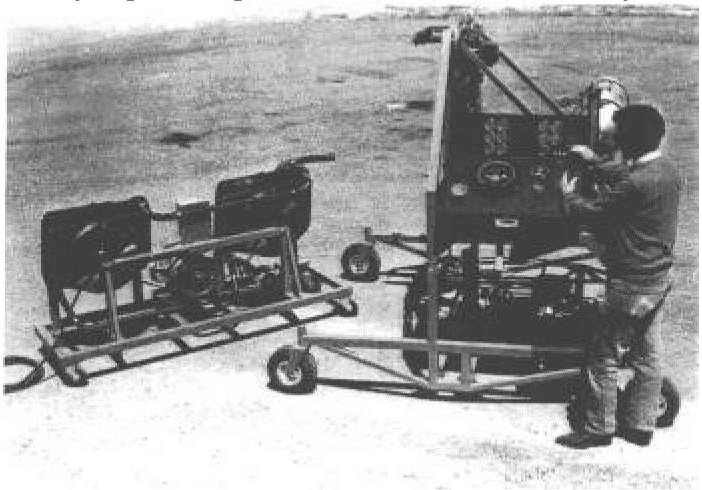
LOW FREQUENCY TORSIONALS

The vibration characteristics of the new prototype system were quite different from the previous systems. One could tell something radical had changed. The resonant point had been lowered below 600 RPM, the starting RPM of the engine. With such a low frequency and high amplitude of vibration, it was possible to visually hear and see the resonance occurring. One could see torque reversals occurring at the prop. The aircraft would violently shudder and shake itself apart, if allowed to continue. As the throttle was advanced, the RPM would get hung-up at the torsional point. Les could give it full throttle and it would just soak up all the energy from the engine, preventing the RPM from going through the torsional barrier. Occasionally, more by chance than anything, the RPM would pass through the resonance and then become super, super smooth. Likewise, when the engine was shutdown, the RPM would momentarily hang-up at the resonance point. All of a sudden, the plane would shudder and shake until all the energy of momentum was used up. Then the propeller would stop rather abruptly. It was the weirdest thing.

Although we were successful in moving the torsional resonance point to a lower energy level, we had not eliminated the problem. Numerous experiments and tests were tried. At times, we were able to go into resonance with the ignition and fuel off using only the electric starter. About the same amount of shudder and vibration was produced through the aircraft when excited by the engine compression alone, as it did when the engine was running under its own power in resonance. At this point, we started to realize we had something here that was really mysterious. This led to an experiment where we replaced the two spark plugs with compression release valves, hooked up to a common control handle. With the engine and system turning over using the starter alone, the vibration and shudder in the plane instantly disappeared and became as smooth as silk, as soon as we opened the compression release valves. As soon as we would close the valves, the vibration and shudder would return. We could start and stop the resonance at will. Clearly, it could be seen that the resonance could be excited by compression strokes alone. The thing that blew our minds was that even when the input energy was low, the output loads were still as destructive to the airframe as when the input energy was high

INFINITE LOADS?

When we started to look into torsional resonance theory we found an explanation. Without any damping in the system, theoretically the peak load at resonance reaches infinity. That's why the input load had very little effect on the output load. Now many have said that it was just theoretical and there is no situation where any material would have zero damping qualities. Well, how much was the damping effect? We do not really know at this point. If the damping were to bring the load down to one tenth of infinity, that would still be a big load. What I am getting at is this: The loads are very high during resonance and are not entirely dependent on the input load.

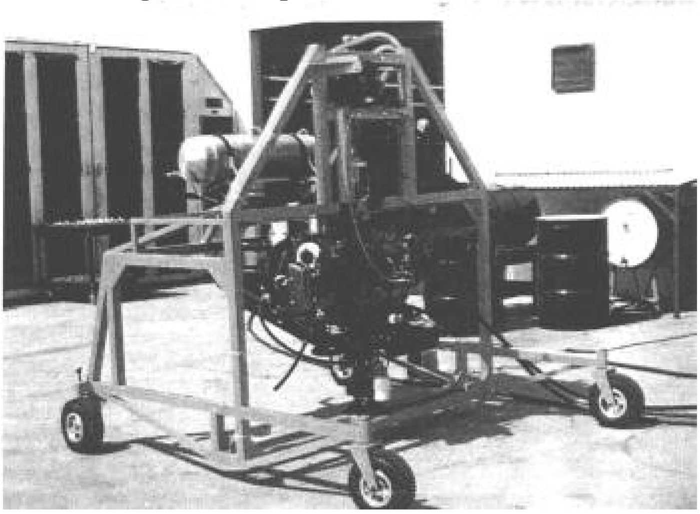


THE FREEWHEEL CLUTCH

The idea for a freewheel clutch came from our machinist, Ray Johnson, and I must give him the credit.

He came in one day and told me that when he was a kid, his dad had a thrashing machine on the farm They would run the belt from the tractor to the thrashing machine and it had a freewheel device on it so that any vibration coming from the old two cylinder John Deere would be somehow taken care of. The minute he said "freewheel clutch", it rang a bell. After previously seeing the oscillating torque reversals of the prop I knew we needed some way to allow a torque reverse to occur without the bounce back. I had been looking at centrifugal clutches, manual clutches, etc. that could be used to disengage and allow some slip. We even tried a test with a super loose belt with idler pulleys but the slop still wasn't enough. The torsional amplitude was just too great at the low system frequency we were dealing with.

Immediately after Ray mentioned the freewheel clutch, I started investigating and found a Borg Warner clutch that was used in automatic transmissions It was a double cage, full phasing sprag clutch. The double cage caused all the little cams inside to engage precisely at the same time. I had previously had experience with freewheel roller type clutches at Avian but we had problems with the brinelling of the clutch races when one roller would engage before the others and momentarily take the full torque, causing eventual clutch failure. The double cage full phasing, sprag clutch solved this problem.



It took a month or two to design and have the clutch parts made. The clutch itself was mounted on the front of the upper plastic sprocket. It had its own bearing to maintain the clutch concentricity. The inner clutch race was integrated with the collar that transferred the torque to the upper 1" shaft. The heat treating for the clutch races and collet was somewhat complicated and expensive but at that point we weren't looking at the cost, as much as just trying to find something that was lightweight and workable.

At that time I was under tremendous pressure at Bede to try to get this system working. After a lot of hard work the parts were made, everything went together beautifully and the clutch was mounted in the airplane. About that time, our engine company had some problems and we could not get any engines. I had the drive system in the ship shortly after New Years but it sat until sometime in March before we were able to get an engine to test it. So, I was sitting that whole time wondering if it would work. Finally the engine arrived. The mechanics installed it and started it up. It was super smooth. There was no sign of any shudder or vibration in the aircraft due to torsionals. The first tests were so successful that Les took the plane up. He came back with a big smile on his face and told us it was the smoothest drive system he had ever flown. Jim was relieved and happy, like, real happy! We had solved the torsional problem.

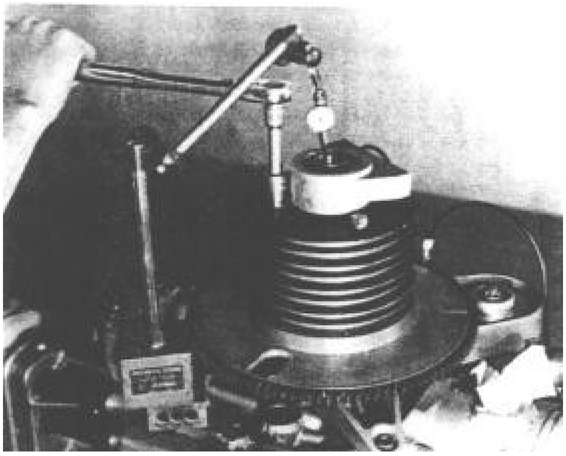
Dyno test stand used for RotorWay engine development, air show demonstrations, and production engine run-ins.

DUAL FREQUENCY SYSTEM

According to theory when the stiffness of a given system goes to zero, the resonance point also goes to zero RPM. With the freewheel clutch, the torsional frequency would go to zero whenever a torque reversal occurred For that moment in time, the RPM would then be above the resonance point and the engine would have no problem powering up into the operating RPM range. In this regard, the BD-5 soft system with the freewheel clutch was a passive dual frequency system, that functioned much like the active dual frequency system used in the Continental Tiara family of geared aircraft engines

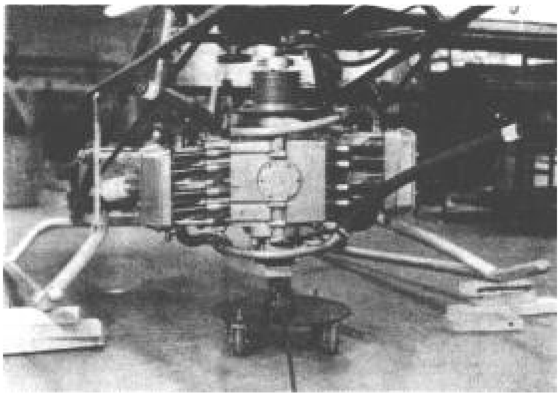
FREEWHEEL CLUTCH - PARTIAL SOLUTION!

It must be understood that the freewheel clutch is only part of the solution to the torsional resonance problem. Lowering the resonant point below the starting RPM of the engine is the other essential part of the solution. Simply installing a freewheel clutch in a system, where the torsional resonance point is still in the operating range, may give the appearance of success for the short term but not for the long term. In a low frequency, torsionally soft system like that developed at Bede, the clutch chatter frequency is low and the amplitude of rotational vibration is high, as the RPM passes through the resonance point. Also, this occurs at the point when the engine is just about to start and the energy level in the system is quite low.



Excerpt from professional Rotorway operation and maintenance manual which contains detailed step by step instructions. This photo shows a setup for checking drive pulley run-out. A model publication for auto conversions

It is true, the loads can be very high at the resonance point, but this occurs during a torque reversal which disengages the clutch and causes these loads to go to zero. These characteristics are good for long clutch life, which means a smaller clutch with a lower capacity is all that's required. This saves both weight and cost. On the other hand, in a higher frequency, torsionally hard system, the clutch chatter frequency is high and the amplitude of rotational vibration is low. With this type of system, the energy level is high. These characteristics tend to shorten clutch life. A system of this type will require a clutch with a much higher capacity, since torsional resonance is still a problem. The clutch and all other drive system components will then be subject to limited life considerations. I know of many who have tried using a freewheel clutch in a hard system as the solution to the torsional resonance problem, but I do not know any who have succeeded in the long term. For these reasons, I can not recommend the use of a freewheel clutch with a torsionally hard system



161 photos and 10 drawings throughout the manual fully illustrate the operation and maintenance of the RW133 engine. This picture suggests an acceptable method for installing the engine in the airframe.

LATERAL VIBRATION PROBLEMS

Although we had solved the torsional vibration problem at Bede, lateral vibration problems still needed to be addressed. They had set up a test stand in an old gutted mobile home beside the Bede shop and the engine mechanic who was an expert in two-cycle engines was doing a lot of experimenting to improve the engine One day he and his assistant were working right beside the engine, in front of everything. The lower jackshaft was turning about 6000 RPM and he was adjusting the carburetors when he stepped aside slightly to get a wrench. All of a sudden there was a big explosion and a hole appeared in the wall of the test stand building. The lower jackshaft had broken loose from its rubber couplings and was hurled like a missile through the wall. It travalled almost to the next building, nearly going through the wing of a Beech 18 and then burying itself in the Kansas gumbo mud. The energy involved was just unbelievable. If the mechanic had been standing where he had been just seconds before, he would have been killed. Once the system was put back together, we ran it with a strobe light on the jackstand. Immediately we saw that the lower jackshaft was not maintaining its concentricity with the engine crank on the forward end nor the sprocket on the aft end. The rubber couplings were too soft. The system was modified to use spherical bearings on each end to locate the lower jackshaft so it would not start this lateral vibration due to the centrifugal force acting on the shaft. This change solved this problem.

There was also a lateral vibration problem with the lower sprocket. After hooking up the strobe light, we found the lower sprocket support was putting an undulating wave of vibration into the rear bulkhead of the engine compartment. This explained why all the rivets on the outside skin at that bulkhead were always coming loose. One day this vibration was particularly bad and we had Burt come by to take at look it. When he saw it, he just looked sort of shocked, turned white and went off mumbling something about not letting Les see this because we'll never get him to fly it again. I think it was at that point that he sort of gave up. This, along with the many other problems with the engine seemed to be the last straw as far as Burt was concerned. It was about a week or two later that both Burt and I left Bede Aircraft. Before my last day, I turned the design responsibility for the drive system over to our landing gear man, Al Thompson. I gave him instructions on how to redesign the lower sprocket mount. He did a superb job and the new mount solved the lateral resonance problem in the lower sprocket.

ROTORWAY

While at RotorWay, B.J. Schramm assigned me the job of designing and building a water dynamometer test stand for the RW 133 helicopter engine. The engine was mounted vertically; just like it was in the helicopter. The dynamometer had a fairly heavy, high inertia rotor and was connected to the engine by a drive shaft with two universal joints. This test stand was used not only to develop the engine but to later fully test and run each customer's engine before delivery. The test stand was designed and built with a good appearance so that it could be used at Oshkosh and other air shows to demonstrate the engine, showing the actual torque and horsepower output to potential customers.

One day, while testing the engine, all hell broke loose. The jackshaft with the two universals had broken off the engine and was flailing around, shaking the test stand quite violently. If I had been anywhere close, I would not be among the living today. We found that the upper part of the crankshaft had broken off. The break was all crystalline and it had the characteristics of a torsional fatigue failure. I mentioned to B.J. that the crank material sure looked strange. That was when I found out the crank was cast iron. The RotorWay engine was based on the Volkswagen engine but was highly modified to produce the power required for the helicopter. Although the Volkswagen engine had a forged crank, the RotorWay engine required a special crank with a long stroke. Since the engine was only in the development phase, B.J. used a cast iron crank. Soon after this failure, B.J. had a new forged crank developed to replace the cast iron crank. One thing for sure, a cast iron crankshaft is not the best way to go, when trying to deal with torsional vibration.

CLUTCH SPRING SOLUTION

B.J. got in touch with the people who manufactured the dynamometer and found out that hooking a 4-cylinder engine to one of these dynos can be a problem. Any engine that produces 2 power strokes per revolution is bad news when it comes to torsional vibration, we were told. They suggested installing clutch springs, from an automobile clutch assembly, between the engine and the water dynamometer to solve this torsional problem. (This is the same idea Lou Ross uses on his gear boxes.) We also put a guard around the jackshaft so that if another failure occurred it would be contained I saw the test stand a few years ago and it appeared to be in good shape and still in use. The spring idea seemed to have worked out.

DRIVE SYSTEM CONFIGURATIONS

Any time a propeller is connected to an engine in any way other than directly to the crank it would be wise to realize that torsional vibration can be a problem. Basically, there are three propeller drive system configurations:

1. Propeller speed-reduction unit alone
2. Propeller speed-reduction unit with a shaft drive
3. Propeller shaft drive alone

TORSIONAL RESONANCE FREQUENCY

$$k = \frac{T}{a} = \frac{\pi d^4 G}{32L}$$

- Where k is the torsional spring constant, i.e. the torque (T) required to produce an angle of twist (a) of 1 radian in the shaft to which the propeller is attached.
- Where d is the diameter of the propeller shaft.
- Where G is the shearing modulus of elasticity of the shaft material
- Where L is the length of the shaft in inches.

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{I}} = \frac{1}{2\pi}\sqrt{\frac{\pi d^4 G}{32IL}}$$

- Where f is the frequency of the torsional vibration.
- Where I is the mass moment of intertia at the propeller

From the above formula it can be seen that:

The torsional frequency can be lowered by:

1. Decreasing the diameter of the shaft(s) (d)
2. Decreasing the shearing modulus of elasticity of the shaft material (G)
3. Increasing the mass moment of inertia of the prop (l)
4. Increasing the length of the shaft (L)

The torsional frequency can be raised by:

1. Increasing the diameter of the shaft(s) (d).
2. Increasing the shearing modulus of elasticity of the shaft material (G).
3. Decreasing the mass moment of inertia of the prop (l).
4. Decreasing the length of the shaft (L).

Torsional resonance frequency is affected, more or less, by the propeller, engine crankshaft, connecting rods, pistons, and every part in between such as a flywheel, gears, belts, and, to a lesser extent, the valve train and accessories.

TYPES OF DRIVE SYSTEMS

1. A dampened system is one that uses a vibration damper to lower the resonant loads to more acceptable levels, while leaving the torsional resonance frequency within the operating RPM range of the engine. A dampened system can be used with a propeller speed-reduction unit and/or a drive shaft (i.e. Molt Taylor).

2. A hard drive is one that has a high torsional spring constant (k) and no slop from the propeller through to the engine crankshaft (maximum rigidity). The torsional problem is overcome strength and maximum stiffness. If a belt is used it should be tensioned as per manufacturer's recommendations. (i.e. Dave Blanton type bed drive system). A hard system becomes prohibitively heavy when used with a shaft drive because of the high torsional loads involved.

3. A soft system is one that has a low torsional spring constant (k) from the propeller through to the engine crankshaft so as to move the torsional resonance frequency below the operating RPM range and preferably below the starting RPM of the engine. A soft system, using a propeller speed-reduction unit alone (no driveshaft) with a sufficiently low torsional spring constant, would be difficult to design because of space, weight, and engineering limitations. A soft system with a drive shaft, if properly designed and tested, has the potential of being the lightest and most reliable of all the systems discussed (i.e. BD-5 belt/shaft drive system).

DESIGN CRITERIA RECOMMENDATIONS

1. The more cylinders the better!

2. Engine Crankshaft:

-1 st choice > forged
- 2nd choice> machined billet
- Not the best choice > cast iron

3. Joints in Rotating Parts:

- Use joints that transfer torque by faction where possible (i.e. shrink, press &/or tapered fits)
- Splines are not the best choice in hard systems.
- If bolted joints (i e. flanged) are used, do not use the allowable bolt shear strength to carry the engine torque through the joint. Instead, size the bolts so that they can be tightened to produce sufficient bolt tension so the engine torque can be transferred through the joint by the resulting friction between the flanges (Note: It would not be a good idea to have any bolt threads in the vicinity on the joint.)

4. System Slop:

- In a "hard system" (i.e. Dave Blanton hypesystem) avoid any slop in the system Use a belt with proper tension as per manufacturers recommendations.
- In a 'soft system" (i.e. the BD-5 system) some slop can be tolerated. If a toothed belt (i.e. HTD) is used, it can be run loose. Also, gears and splines are less critical (i.e. the Continental Tiara aircraft engine). If a silent link type chain is used, chain tension would be less critical.

5. Torsional Spnng Constant of the System

- In a "hard system" (i.e. Dave Blanton type system) the main design criteria should be to achieve a high torsional spring constant without adding excessive weight. The torsional problem is overcome by brute strength and maximum stiffness
- In a "soft system" (i e. the BD-5 system) the main design criteria should be to achieve a low torsional spring constant while meeting the torque requirements of the

engine with a moderate safety factor. The torsional spring constant should be low enough to move the torsional resonance frequency below the starting RPM of the engine.

- The torsional spring constant can be lowered by decreasing the diameter of the shaft(s), decreasing the shearing modulus of elasticity of the shaft material, increasing the mass moment of inertia of the propeller and by increasing the length of the shaft(s).

6. Freewheel Clutch:
   - Use only a double cage, full phasing, sprag type clutch. This type of clutch works well with a "soft system".
   - Roller and uncaged spring-loaded type freewheel clutches are not recommended.
   - It is not recommended to use a freewheel type clutch with a "hard system." The higher energy level of resonance, in this type of system, will eventually destroy the clutch, even though the engine RPM only passes through the resonance when going up to or down from the normal operating speed.
7. Cantilever Shafts:
   - Mounting overhung belt sprockets or gears on cantilevered shafts should be avoided, particularly on a "hard system".
   - If a design requires an overhung sprocket, keep the offset and the belt width to a minimum.

SUMMARY

BECOME FULLY INFORMED BEFORE TACKLING TORSIONALS !

It would be advisable to develop a good base of knowledge before becoming too involved in torsional problems. Most intuitive solutions are the opposite of what should actually be done when torsional resonance is involved. It is my hope that this article will bring a degree of caution to experimenters and will encourage them to seek out more knowledge on the subject before they jump in and waste a lot of their time and money.

Demonstration of torsional resonance effects. A 2x4 representing the inertia of a propeller is powered by a cordless drill motor through a 3/32 inch piano wire ("soft" system). One end of the rod is bent 90 degrees and stapled securely to the wood. Energy is applied by short, rapid trigger squeezes to simulate engine power pulses. Torsional effects are visual and are heard from the slippage of the shaft in the chuck and torque reversal clicking of the gears.